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Spacetime-Filling Branes and Strings with Sixteen Supercharges

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Abstract

We discuss branes whose worldvolume dimension equals the target spacetime dimension, i.e. 'spacetime-filling branes'. In addition to the D9-branes, there are 9-branes in the NS-NS sectors of both the IIA and IIB strings. Each of these types of branes is used in the construction of a string theory with sixteen supercharges by modding out a type II string by an appropriate discrete symmetry and adding 32 9-branes. These constructions are related by a web of dualities and each arises as a different limit of the Hořava-Witten construction.

1. Branes and Charges

It is by now well understood that there is an intricate relationship between the 'central' charge structure of the spacetime supersymmetry algebra and the spectrum of BPS states that are described by supersymmetric brane solutions [1]. The generic rule is that a p-form charge in D dimensions contains the charges for a p-brane and a $(D-p)$-brane [2, 3]. This gives rise not only to the well-known BPS spectrum of type II string theory and M-theory but also to extra 9-branes. These 9-branes are the 'spacetime-filling branes' mentioned in the title. This talk discusses their role in string theory. Below we first discuss the different supersymmetry algebras with 32 supercharges in ten and eleven dimensions.

The ten-dimensional IIA supersymmetry algebra with central charges is given by ($\alpha = 1, \cdots, 32;\ M = 0, \cdots, 9$):

$$\begin{aligned}\{Q_\alpha, Q_\beta\} &= \left(\Gamma^M C\right)_{\alpha\beta} P_M + (\Gamma_{11} C)_{\alpha\beta}\, Z + \left(\Gamma^M \Gamma_{11} C\right)_{\alpha\beta} Z_M \\ &\quad + \tfrac{1}{2!}\left(\Gamma^{MN} C\right)_{\alpha\beta} Z_{MN} + \tfrac{1}{4!}\left(\Gamma^{MNPQ}\Gamma_{11} C\right)_{\alpha\beta} Z_{MNPQ} \\ &\quad + \tfrac{1}{5!}\left(\Gamma^{MNPQR}\Gamma_{11} C\right)_{\alpha\beta} Z_{MNPQR}\,.\end{aligned} \tag{1}$$

Note that the right-hand-side contains the maximum number of allowed central charges:

$$\tfrac{1}{2} \times 32 \times 33 = 1 + 10 + 10 + 45 + 210 + 252\,. \tag{2}$$

Scanning the known IIA branes we find the following correspondences between charges and BPS states:

$$\begin{aligned} P_M &\to \text{W}-\text{A}\,, \\ Z &\to \text{D0}\,, \end{aligned}$$

$$\begin{array}{rcl} Z_M & \rightarrow & \text{NS}-1\text{A and NS}-9\text{A}\,, \\ Z_{MN} & \rightarrow & \text{D2 and D8}\,, \\ Z_{MNPQ} & \rightarrow & \text{D4 and D6}\,, \\ Z_{MNPQR} & \rightarrow & \text{NS}-5\text{A and KK}-\text{A}\,. \end{array} \tag{3}$$

We find a gravitational wave (W–A), a fundamental string (NS–1A), Dp-branes ($p=0,2,4,6,8$), a solitonic five-brane (NS–5A), a Kaluza-Klein monopole (KK–A) and a nine-brane (NS–9A). All cases are well understood except for the NS–9A brane, which corresponds to a spacetime–filling brane in IIA string theory [2].

We next consider the ten-dimensional IIB supersymmetry algebra with central charges. In this case there are two Majorana-Weyl charges Q^i_α $(i = 1, 2)$ with the same chirality. The algebra is given by

$$\begin{aligned} \{Q^i_\alpha, Q^j_\beta\} \;=\; & \delta^{ij}\left(\mathscr{P}\Gamma^M C\right)_{\alpha\beta} P_M + \left(\mathscr{P}\Gamma^M C\right)_{\alpha\beta} Z^{ij}_M \\ & + \tfrac{1}{3!}\varepsilon^{ij}\left(\mathscr{P}\Gamma^{MNP} C\right)_{\alpha\beta} Z_{MNP} + \tfrac{1}{5!}\delta^{ij}\left(\mathscr{P}\Gamma^{MNPQR} C\right)_{\alpha\beta} Z^{+}_{MNPQR} \\ & + \tfrac{1}{5!}\left(\mathscr{P}\Gamma^{MNPQR} C\right)_{\alpha\beta} Z^{+,ij}_{MNPQR}\,. \end{aligned} \tag{4}$$

Here $\mathscr{P}$ is a chiral projection operator and Z^{ij}_M, $Z^{+,ij}_{MNPQR}$ are doublets of SO(2) (symmetric traceless representations). The upper index $+$ indicates that the charge is a self-dual 5-form. As in the IIA case we have the maximum number of p-form charges:

$$\tfrac{1}{2} \times 32 \times 33 = 10 + 20 + 120 + 126 + 252\,. \tag{5}$$

Scanning the known IIB branes we find the following correspondences:

$$\begin{array}{rcl} P_M & \rightarrow & \text{W}-\text{B}\,, \\ Z^{ij}_M & \rightarrow & \text{D1 and NS}-1\text{B}\,, \\ & & \text{D9 and NS}-9\text{B}\,, \\ Z_{MNP} & \rightarrow & \text{D3 and D7}\,, \\ Z^{+,ij}_{MNPQR} & \rightarrow & \text{D5 and NS}-5\text{B}\,, \\ Z^{+}_{MNPQR} & \rightarrow & \text{KK}-\text{B}\,. \end{array} \tag{6}$$

In this case we find a gravitational wave (W–B), a fundamental string (NS–1B), Dp-branes ($p = 1, 3, 5, 7, 9$), a solitonic five-brane (NS–5B), a Kaluza-Klein monopole (KK–B) and a further nine-brane (NS–9B). We see that the IIB central charges suggest the existence of two spacetime-filling branes: the D9-brane and the NS–9B brane. The first one has been discussed in the context of D-branes (see e.g. [4]), and the second occurs in the work of [2]. All cases are well understood except for the NS–9B brane.

Finally, we consider the eleven-dimensional supersymmetry algebra ($\alpha = 1, \cdots, 32$; $M = 0, \cdots 10$):

$$\{Q_\alpha, Q_\beta\} = \left(\Gamma^M C\right)_{\alpha\beta} P_M + \tfrac{1}{2!}\left(\Gamma^{MN} C\right)_{\alpha\beta} Z_{MN} + \tfrac{1}{5!}\left(\Gamma^{MNPQR} C\right)_{\alpha\beta} Z_{MNPQR}\,. \tag{7}$$

Again, the algebra contains the maximum number of allowed central charges:

$$\tfrac{1}{2} \times 32 \times 33 = 11 + 55 + 462\,. \tag{8}$$

These central charges are related to the following M-branes:

$$\begin{aligned} P_M &\rightarrow \text{W}-\text{M}\,,\\ Z_{MN} &\rightarrow \text{M2 and M9}\,,\\ Z_{MNPQR} &\rightarrow \text{M5 and KK}-\text{M}\,. \end{aligned} \tag{9}$$

We find a gravitational wave (W–M), a membrane (M2), a five-brane (M5), a Kaluza-Klein monopole (KK–M) and a nine-brane (M9). For a recent discussion of the M9-brane domain wall solution, see [5]. Note that in this case we do not find any spacetime-filling branes.

All branes mentioned above can be related to each other via T-duality, S-duality and/or dimensional reduction. Formally, the D9-brane is obtained from the other D-branes by T-duality, the NS-9B brane is obtained from the D9-brane by S-duality, and the NS-9A brane is obtained from the NS-9B brane by T-duality. Finally, the M9-brane provides the 11-dimensional origin of both the D8-brane and the NS-9A brane. This is formal, as it is usually not consistent to have a single D9-brane, and the same will apply to the other 9-branes related to this by duality. However, it is consistent to have 32 D9-branes together with an orientifold plane in the construction of the type I string, and in this talk I will discuss the analogous constructions involving the other 9-branes to give the various superstrings with sixteen supercharges, and show that they are related to the type I construction by the appropriate S and T dualities.

2. String theories with 16 supercharges

We have seen how the central charge structure of the IIA/IIB and M-theory superalgebras give rise to three ten-dimensional space-time filling branes: the D9-brane, the NS–9B brane and the NS–9A brane. All three branes are related to each other via T- and/or S-duality. It is well-known that the D9-brane is related to the Type I SO(32) string theory as follows. Consider the operator Ω acting on the perturbative IIB theory through the worldsheet parity reversal of the fundamental string (NS–1B brane):

$$\Omega: \qquad \sigma \longrightarrow \pi - \sigma\,. \tag{10}$$

In orientifolding by Ω, it is necessary to add 32 coincident D9-branes to cancel the anomalies and tadpole introduced by the O9 orientifold fixed plane, and this gives the Type I SO(32) string theory. However, the Type I SO(32) string theory is related, via duality and/or reduction, to other string theories with sixteen supercharges and this suggests that one might also be able to describe these other $N = 1$ superstring theories by dividing out Type IIA or IIB string theory by a discrete symmetry, with the addition of a set of spacetime-filling branes in order to cancel the anomalies introduced by the projection. In [2, 6], it was argued that the $SO(32)$ heterotic string can be obtained by modding out the IIB string with a (non-perturbative generalisation of) the operator $(-1)^{F_L}$ (where F_L is the left-moving fermion number) in the presence of 32 NS-9B branes. This can be generalised to other cases and the relevant perturbative symmetries of Type IIA/IIB string theories responsible for the projections onto the various string theories with sixteen supercharge can be identified via duality.

This leads us to *define* the discrete symmetries

$$\tilde{\Omega} = S\Omega S^{-1}, \qquad \hat{\Omega} = T\tilde{\Omega}T^{-1}, \qquad I_{10}\Omega = T\Omega T^{-1}\,, \tag{11}$$

where I_{10} is reflection in the x^{10} direction. It can be argued (see [7]) that each string theory with sixteen supercharges arises from a theory with 32 supercharges on modding out by a $\mathbb{Z}_2$ symmetry, in a background with 16 9-branes (plus their 16 mirror images). The type I theory arises from modding out the IIB string by the world-sheet parity Ω with 32 D9-branes, and then the others arise from acting on these constructions with T and S dualities. The set of discrete symmetries obtained in this way and used in the construction of the string theories with sixteen supercharges are given by

$$\begin{aligned} \text{Type I SO}(32) \quad &\Leftrightarrow \quad \Omega\,, \\ \text{Type I}'\ \text{SO}(16)\times\text{SO}(16) \quad &\Leftrightarrow \quad I_{10}\Omega\,, \\ \text{Heterotic SO}(32) \quad &\Leftrightarrow \quad \tilde{\Omega}\,, \\ \text{Heterotic E}_8\times\text{E}_8 \quad &\Leftrightarrow \quad \hat{\Omega}\,. \end{aligned} \tag{12}$$

For more details and arguments in favour of the above suggested constructions, we refer to the paper [7] on which this talk is based.

3. Relation with M-Theory

It turns out that the constructions of string-theories with 16 supersymmetries can all be lifted to M-theory, and that they all arise as particular limits of the Hořava-Witten picture of M-theory compactified on $\mathbb{R}^{8,1} \times S^1 \times S^1/\mathbb{Z}_2$ [8].

Consider first M-theory compactified on a 2-torus with radii R_{10}, R_{11}. When one of the radii is large and the other small, the theory is described by a weakly coupled IIA string theory; for example, if R_{11} is small, this is a IIA string theory with coupling constant $g_{IIA} = (R_{11}/l_p)^{3/2}$ compactified on a circle of radius R_{10}. If both radii are small, then the theory is IIB string theory with coupling constant $g_{IIB} = R_{11}/R_{10}$ compactified on a circle of radius $R_{IIB} = l_p^3/R_{10}R_{11}$. The limit in which $R_{10}, R_{11} \to 0$ gives the IIB string in 10 dimensions [9].

The conjectured $\mathbb{Z}_2$ symmetry of M-theory used in the Hořava-Witten construction is $I_{10}\Omega_M$ where I_{10} takes $x^{10} \to -x^{10}$ and Ω_M reverses the orientation of the M2-brane and the M5-brane and acts in the supergravity as $C \to -C$ where C is the 3-form potential. For M-theory compactified on a 2-torus with radii R_{10}, R_{11}, this symmetry reduces to the various string theory symmetries considered in (12) in the respective string theory limits. If R_{11} is large and R_{10} is small, $I_{10}\Omega_M$ acts as the symmetry $\hat{\Omega}$ of the IIA string, acting as $(-1)^{F_L^c}$ in the perturbative theory. If R_{10} is large and R_{11} is small, on the other hand, $I_{10}\Omega_M$ acts as the symmetry $I_{10}\Omega$ of the IIA string compactified on a circle of radius R_{10}, where Ω is the IIA string world-sheet parity operator. If both radii are small and the IIB string is weakly coupled, so that $g_{IIB} = R_{11}/R_{10}$ is small, $I_{10}\Omega_M$ acts as Ω, the IIB string world-sheet parity operator, while for strong coupling, the theory is the dual IIB string theory with coupling $\tilde{g}_{IIB} = R_{10}/R_{11}$ and $I_{10}\Omega_M$ is the IIB string symmetry $\tilde{\Omega}$, which acts as $(-1)^{F_L}$ in the perturbative theory.

The M-theory construction gives a non-perturbative picture of both the IIA and IIB theories, and shows that the discrete symmetries given in (12) all extend to the same symmetry of the non-perturbative theory, namely the Hořava-Witten symmetry. In particular, we see that $\tilde{\Omega}$ is indeed the strong coupling limit of Ω.

Consider M-theory on T^2 modded out by $I_{10}\Omega_M$. The circle in the x^{10} direction becomes the interval $S^1/\mathbb{Z}_2$ and the torus is replaced by a cylinder. It was argued in [8] that in the limit $R_{11} \to \infty$ and $R_{10} \to 0$ this gives the $E_8 \times E_8$ heterotic string, in the limit $R_{10} \to \infty$ and $R_{11} \to 0$ this gives the type I' string and in the limit in which $R_{11} \to 0$ and $R_{10} \to 0$, this gives the type I string with coupling $g_I = R_{11}/R_{10}$ if this is small, and the $SO(32)$ heterotic string with coupling $\tilde{g}_{het} = R_{10}/R_{11}$ if this is small.

Comparing with the above, the Hořava-Witten construction reduces, in each of the string theory corners of the moduli space, to the different string theory constructions suggested by (12). In the corner in which R_{10} is large and R_{11} is small, the Hořava-Witten construction reduces to orientifolding the IIA string with $I_{10}\Omega$ to obtain the type I′ string, while in the corner in which R_{10} is large and R_{11} is small, the Hořava-Witten construction reduces to modding out the IIA string by $\hat{\Omega} \sim (-1)^{F_L^c}$ to obtain the heterotic string. If both R_{10} and R_{11} are small, then if R_{11}/R_{10} is small the construction gives the orientifolding of the IIB string with Ω to get the type I string, while if it is large it gives the IIB string modded out by $\tilde{\Omega} \sim (-1)^{F_L}$ to give the SO(32) heterotic string. In each of these constructions the 9-branes play a vital role. For a discussion of the the individual cases, see [7].

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